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LABORATORY EXPERIMENTS TO INVESTIGATE EFFECTS AND CAUSES OF DOP--ETC(U)
OCT 66 L STRAUSS, P H HAWKES
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This memorandum describes a study undertaken to analyze in detail a signal-processing phenomena observed during sea tests and in the Laboratory. It has been prepared to show others at NEL the extent of these effects in the particular signal-processing system used. Limited outside distribution is contemplated. This memorandum presents the results of a portion of continuing work on problem number E119.

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LABORATORY EXPERIMENTS TO INVESTIGATE EFFECTS AND CAUSES OF DOPPLER SPREADING IN HETERODYNE CORRELATORS

1.0 PURPOSE OF STUDY

It has been reported in various publications and observed during recent sea trips that in a heterodyne correlator system such as employed by the LORAD equipment[1] correlation pulses (obtained as a result of target detection) can and do appear simultaneously on more than one comb-filter tooth.

During two local sea trips, analog tape data was taken of ten adjacent comb-filter teeth to observe these effects. When these tapes were reproduced in the Laboratory and recorded on Visicorder tape, spreading of these pulses across several filter teeth was observed.

This laboratory experiment has been undertaken to determine the extent of this spreading effect in the controlled environment of the Laboratory, thus getting away from possible sea medium effects.

Prior to the sea trip experiment, work on the laboratory signal processor[2] had indicated that frequency spreading can occur even under these "ideal" laboratory conditions. This situation was first noticed during the checkout and debugging phase following extensive modification of the laboratory equipment. The modifications allowed, for the first time, the selection of one of three system sample rates, and provided for the monitoring of individual comb-filter teeth.

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[1] NEL Report 1060, "LORAD Status Report", 9 October 1961, CONFIDENTIAL

[2] Described in NEL Technical Memorandum 846, "Laboratory Instrumentation for Sonar Signal Parameter Studies," by P. H. Hawkes.

It was found that there was a 6 db correlation loss at the lower sample rate (200 Hz) compared with the two higher sample rates (400 Hz and 800 Hz) when processing a zero doppler 100 Hz bandwidth PN signal. An investigation showed that at the 200 Hz sample rate, the correlator output was divided nearly equally between two comb-filter teeth which were located a distance of two teeth on either side of the "zero doppler" tooth. This frequency splitting was not observed at the higher sample rates.

The cause of this problem was traced to slight frequency errors in the correlator's heterodyne oscillators. When the oscillators were replaced with precise frequency sources, the problem disappeared. It was experimentally determined that the optimum difference frequency was 99.85 Hz. This compares favorably with the theoretical value of 99.84 Hz which comes about from the following:

1. The Deltic has a basic clock rate of 1 MHz.

2. The Deltic is mechanized to correlate sixteen signals sequentially for 313 usec each.

3. The sampling period is thus:

$$313 \times 10^{-6} \times 16 = 5008 \text{ usec}$$

(a sampling frequency of approximately 200 Hz)

4. There is storage capacity for 939 bits of information, giving

$$939 \times 5008 \text{ usec} = 4.7 \text{ seconds of stored data}$$

5. The compression factor is:

$$\frac{\text{Time of information read in}}{\text{Time of information read out}} = \frac{939 \times 5008}{313} = 15{,}024$$

6. The input bandwidth is related to the correlator output frequency as:

$$\frac{1.5 \times 10^6}{15,024} = 99.84 \text{ Hz}$$

where 1.5 MHz is the correlator output frequency for zero doppler.

The doppler spreading seen in the sea trip data closely resembled the effects observed during the above described laboratory experiment. Therefore, experiments were undertaken for the purpose of establishing a quantitative measure of the effect of heterodyne difference frequency on correlator output.

This study is comprised of two parts:

(1) Determination of the heterodyne oscillator frequency accuracy requirements (such that a zero doppler target appears on the center tooth of the comb-filter), and

(2) Determination of correlation pulse spreading across the teeth when an artificially-dopplerized target is used.

2.0 PARAMETERS

These experiments have been conducted with the Laboratory Processor using the following system parameters:

Signal Type: Pseudorandom noise

Center Frequency: 1500 Hz

Bandwidth: 100 Hz

Sample Rates: 200, 400, and 800 Hz

Reference Heterodyne Frequency: 1450.00

Signal Heterodyne Frequencies: 1549.00 to 1550.60 Hz

Pseudorandom Noise Generator Frequencies (generating artificial doppler):

3998.50 to 4004.00 Hz (for outputs on from teeth 12 through 23)

3.0 EQUIPMENT

A block diagram of the system is shown in Figure 1. It consists of the Laboratory Processor and Deltic (the latter modified by a Multiplex Buffer providing ability to operate the system at various sample rates); a Frequency Synthesizer, General Radio, type 1161-A; and a Honeywell 1508 Visicorder (12-channel).

4.0 PROCEDURES

4.1 Heterodyne Difference Frequency Accuracy Tests

4.1.1 The equipment was turned on and allowed to stabilize.

4.1.2 A sample rate was chosen.

4.1.3 Comb-filter teeth 12 through 23 were connected to Visicorder channels 1 through 12, respectively.

4.1.4 A reference signal heterodyned at 1450.00 Hz by the Frequency Synthesizer (F.S.) was stored in the Deltic.

4.1.5 The F.S. was then set to about 1549.84 Hz to observe that the system was operating correctly and that correlation spikes were being developed at comb-filter tooth 17.

4.1.6 The F.S. frequency was then varied from 1549.00 Hz to 1550.60 Hz in chosen steps. At each step seven or eight correlation spikes were allowed to be recorded on the Visicorder tape. Points were obtained closer together in the region of 1549.80 to 1549.90 Hz to observe the detail near the middle of the zero doppler area.

4.1.7 The above steps were repeated for the other sample rates of 400 and 800 Hz.

4.2 Artificially-Dopplerized Tests

4.2.1 Steps 4.1.1 through 4.1.3 were performed.

4.2.2 For a signal heterodyne oscillator, the regular 1550.00 Hz crystal oscillator card (with a measured frequency of 1550.28 Hz) was used in the Deltic. The 4000.00 Hz tuning-fork oscillator was used to drive the pseudorandom generator.

4.2.3 The Frequency Synthesizer was set to 1450.45 Hz and used as the reference heterodyne oscillator.

4.2.4 After the above reference was stored in the Deltic, the PN Generator oscillator card was removed and the F.S. disconnected as the reference heterodyne oscillator. The F.S. was then reset to 4001.52 Hz[3] and applied as the PN generator oscillator. Thus the PNG frequency could be varied, acting (in this system) as an artificially-dopplerized target.

4.2.5 The F.S. signal was then varied from 3998.50 to 4004.00 Hz in steps and data taken as in 4.1.6 and 4.1.7.

5.0 DATA ANALYSIS

For each sample rate the Visicorder tapes were analyzed by measuring the recorded correlation pulse amplitudes and averaging these amplitudes for each frequency and for each affected tooth. These averaged amplitudes were then

[3]The actual (measured) frequency developed by the PN generator oscillator card was 4001.52 Hz. This was the zero doppler frequency used.

recorded on matrix charts, Figures 2 and 9. Curves were drawn from this data for each tooth over the frequency range showing relative improvements of the correlation pulse amplitude at the different sample rates.

6.0 RESULTS

6.1 Matrix Chart and Doppler Tooth Curves

6.1.1 From Figures 3 through 7[4] it is seen that varying the signal heterodyne frequency with respect to the reference heterodyne frequency gives a simulated doppler effect. As the difference becomes greater than 99.90 Hz (zero doppler) signals appear on the higher-numbered doppler teeth giving the effect of an opening target. Frequency differences less than 99.90 Hz give the opposite effect.

The comb-filter teeth are seen to peak at about 0.2 Hz (input equivalent doppler) from each other; this being the doppler resolution of the system. It is given by $\frac{1}{T}$ where T is the length of the transmitted pulse (see paragraph 6.3).

6.1.2 Amplitude

Figures 3 through 7 also show the effect of sample rate on correlation pulse amplitude. These amplitudes are compared in Figure 8 and show that considerable improvement in amplitude is obtained at the higher sample rates. This improvement is substantial in going from 200 to 800 Hz (off-zero doppler) because of a "spreading" phenomena which tends to put the pulse energy into more than one tooth, diluting the signal seen on the correct tooth.

---

[4]These figures are of simultaneous results but have been put on separate sheets for clarity.

It was observed that a correlation will always appear on more than one tooth. Depending on the incoming doppler frequency, the signal will either match exactly the center frequency of a particular tooth or be off slightly one way or the other. In the former case, almost all of the signal is seen at the tooth's output with a little seen on adjacent teeth. In the latter case, the signal energy is split among adjacent teeth depending on the incoming frequency and the accuracy of the comb-filter teeth frequencies.

6.2 Heterodyne Difference Frequency Accuracy

It is seen from Figure 5 that the correlation signal on tooth 17 (designated as zero doppler) peaks at 1549.84 Hz for the 200Hz sample rate and about 1549.90 Hz for the 400 and 800 Hz sample rates. Thus, the difference frequency for the signal and reference heterodyne oscillators is 1549.84 - 1450 or 99.84 Hz for the 200 Hz sample rate, which is identical to the calculated value (page 4). At the higher sample rates the difference frequency is somewhat higher (99.90 Hz).

6.3 Heterodyne Frequency Stability

It is desired that a zero doppler target appear only on tooth 17. Stability requirements on the heterodyne oscillators are obtained from the following:

The doppler resolution is $\frac{1}{T} = \frac{1}{4.7\ \text{sec}} = 0.213$ cycles at the input to the system.

It is related to the system output via the compression factor, 15,024, giving an output resolution of 0.213 x 15,024 = 3,200 Hz. Thus, adjacent comb-filter teeth are 3,200 Hz apart. This is the bandwidth of each comb-filter tooth.

The stability of the heterodyne oscillators must be such that under worst case conditions (signal and reference frequencies diverging) the difference frequency be accurate to one-half tooth resolution, or $\frac{0.213}{2} = 0.107$ Hz.

Using 99.90 Hz as the correct heterodyne frequency difference, the signal oscillator would be 1549.90 Hz and the reference oscillator, 1450 Hz. A worst-case condition would put the signal oscillator at $1549.90 + \frac{0.107}{2} = 1549.9535$ Hz and the reference oscillator at $1450 - 0.053 = 1449.9465$ Hz. This gives stability requirements of 0.00345% for the signal and 0.00368% for the reference oscillators.

6.4 Artificially-Dopplerized Signals

Figures 10 through 14 show the effects of varying the PN generator oscillator to simulate dopplerized targets. As the frequency is increased, a closing target is simulated and signals emerge from the lower teeth (with respect to tooth 17). The opposite is true for frequencies less than that required for zero doppler.

6.4.2 Doppler Resolution

Doppler resolution can be obtained in terms of the PN Generator clock frequency as follows:

$$\frac{0.213}{1500} = \frac{f}{4000}$$

$$f = \frac{0.213 \times 4000}{1500} = 0.568 \text{ Hz}$$

It can be seen from the curves that the peaks of adjacent teeth are approximately 0.6 Hz apart. It was also observed that the 200 Hz sample rate caused

a "spreading" effect at off-zero doppler frequencies similar to that described in paragraph 6.1.2. This spreading was seen to become worse as the frequency was raised or lowered from the center frequency of 4001.52 Hz. It was observed that an input signal giving an output at tooth 1 also gave an output on tooth 34 and visa versa.

7.0 CONCLUSIONS

7.1 Heterodyne-Frequency Oscillator Accuracy and Stability

The above discussed data has shown the need for a very accurate difference frequency as derived from the signal and reference heterodyne oscillators. This must be 99.90 Hz for the correlation pulse to appear on tooth 17 for a zero doppler target at sample rates of 400 and 800 Hz. Due to the "spreading effect" seen at the 200 Hz sampling rate, too much amplitude is lost as compared with the higher sample rates. Therefore, this sampling rate should not be used in a heterodyne correlator of this type.

The stability requirements on these oscillators show that in order to have a correlation pulse appear where it should with a particular doppler target, a frequency stability of $\pm 0.003\%$ is required in the worst case.

7.2 Artificially-Dopplerized Targets

With correct heterodyne oscillator frequencies stored in the Deltic, it has been shown that a "spreading effect" is very evident at the 200 Hz sample rate; to the extent that a signal dopplerized to appear at tooth 1 will also appear at tooth 34.

At the 400 and 800 Hz sample rates, correlation pulses will appear on two or three adjacent teeth but will not be spread across large portions of the comb-filter bank.

Recently, the heterodyne oscillators were removed from the Deltic used on the BAYA and measured very accurately. It was seen that they differed by 100.45 Hz instead of the desired 99.84 Hz (at 200 Hz). Thus there was good reason for some of the doppler spreading observed in the sea data. Sea medium effects could account for a portion of this phenomena and will be explored in the future.

Spreading effects at 200 Hz similar to those observed during sea tests have been duplicated in the Laboratory. They can be minimized by having accurate and stable heterodyne oscillators and by using sample rates in excess of 200 Hz.

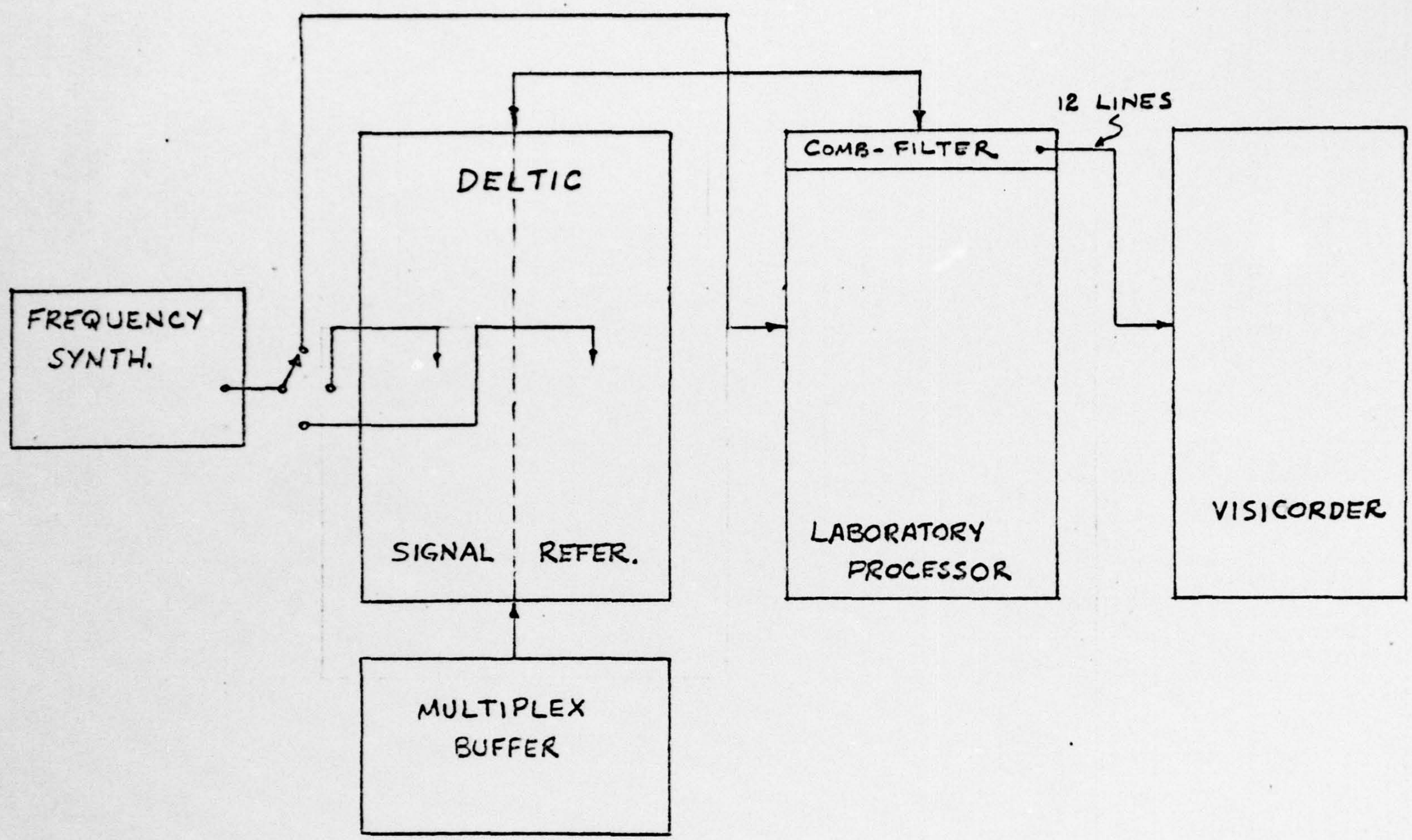

FIG. 1. EXPERIMENT SET-UP

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Tooth	12			13			14			15			16			17			18			19			20			21		
Sample Rate (Hz) / Freq. (MHz)	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800
1550.60				0.85			0.3																		0.85	1.52	1.9	0.45	0.85	1.25
.50				0.33			0.85															0.35	0.7	0.78	0.93	1.62	2.22			0.55
.40							0.9			0.4												0.85	1.42	1.66	0.5	0.93	1.48			
.30							0.63			0.75									0.17	0.75	0.73	0.92	1.62	2.25			0.65			
.20										0.95			0.21			0.12	0.48		0.7	1.52	1.7	0.63	1.1	1.55						
.10										0.7			0.78			0.53	0.68	0.63	0.98	1.88	2.37		0.58	0.65						
													0.95			0.6	0.9	0.93	0.9	1.7	2.22			0.45						
1550.00													0.93			0.9	1.32	1.45	0.69	1.22	1.72									
															0.45			1.75			1.4									
													0.73	0.55	0.48	1.1	1.62	1.9	0.53	0.88	1.15									
															0.53			2.05			1.0									
.90													0.78	0.73	0.63	1.35	1.7	2.02	0.2	0.63	0.8									
													0.78	0.77	0.74	1.48	1.7	2.05			0.66									
													0.78	0.85	0.93	1.48	1.68	2.0			0.55									
													0.78	1.12	1.11	1.50	1.43	1.77	0.19		0.48									
.80													0.82	1.25	1.42	1.45	1.33	1.55			0.43									
												0.45	0.95	1.67	1.92	1.22	0.95	1.05	0.23											
.70											0.65	0.7	0.98	1.72	2.22	1.02	0.7	0.65	0.63											
											0.88	0.85	0.95	1.73	2.25	0.65	0.45	0.48	0.83											
.60										0.56	1.12	1.22	0.88	1.42	1.97	0.28			0.9											
.50								0.6	0.5	0.98	1.72	2.12	0.2	0.73	0.95				0.78			0.6								
.40							0.52	1.02	1.08	0.9	1.48	1.98			0.43	0.22			0.4			0.88								
.30					0.58	0.45	0.83	1.45	2.03	0.3	0.78	1.05										0.7			0.43					
.20				0.48	0.86	0.85	0.83	1.41	2.2			0.5													0.93					
.10			0.48	0.85	1.51	1.87	0.43	0.75	1.22													0.78			0.33					
1549.00		0.69	0.9	0.95	1.34	2.1			0.5																0.33			0.8		

Figure 2. Heterodyne-Frequency Accuracy Matrix

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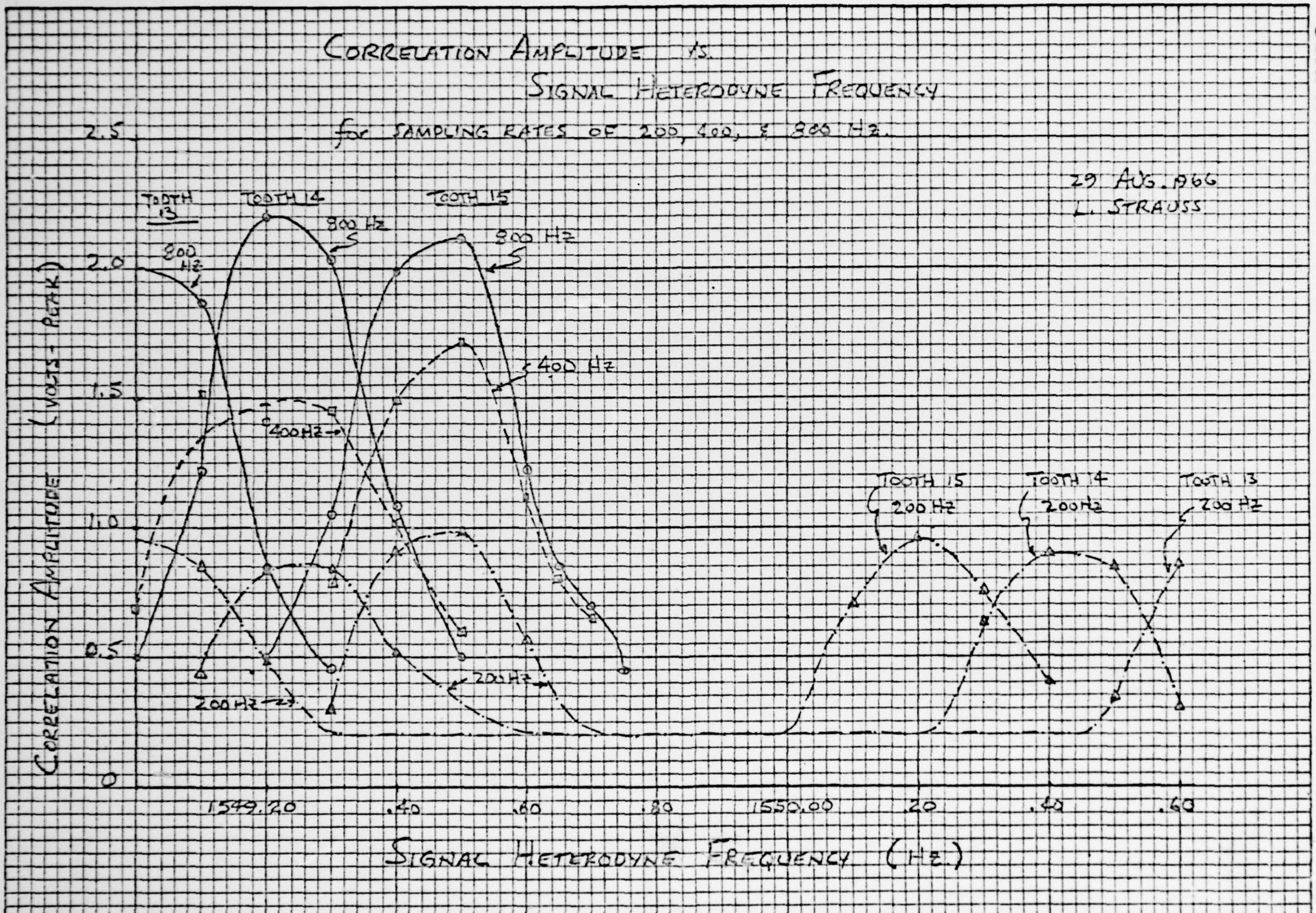

Figure 3. Correlation Amplitude vs. Signal Heterodyne Frequency for Sampling Rates of 200, 400 and 800 Hz for teeth 13, 14 & 15

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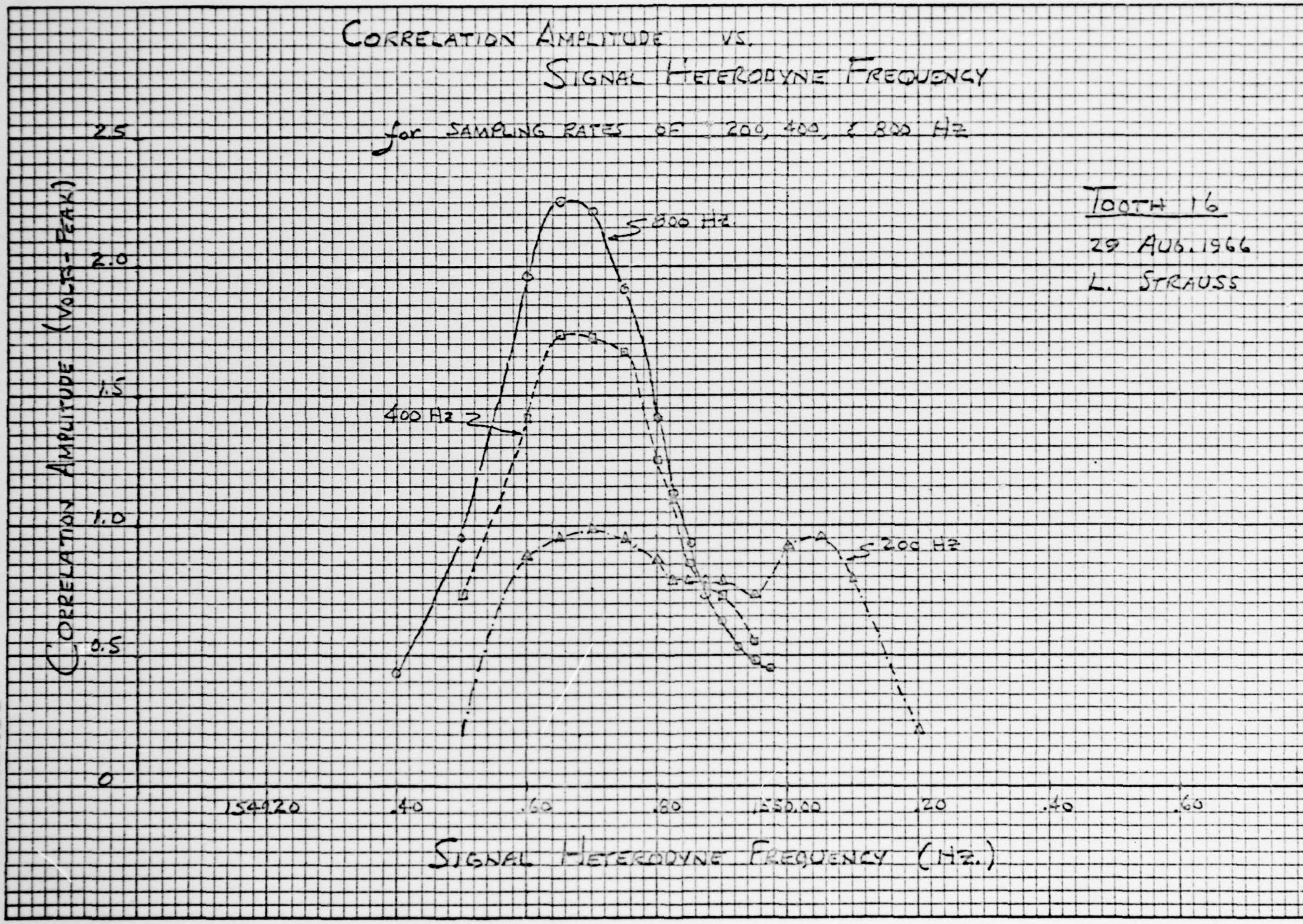

Figure 4. Correlation Amplitude vs. Signal Heterodyne Frequency for Sampling Rates of 200, 400 and 800 Hz for tooth 16

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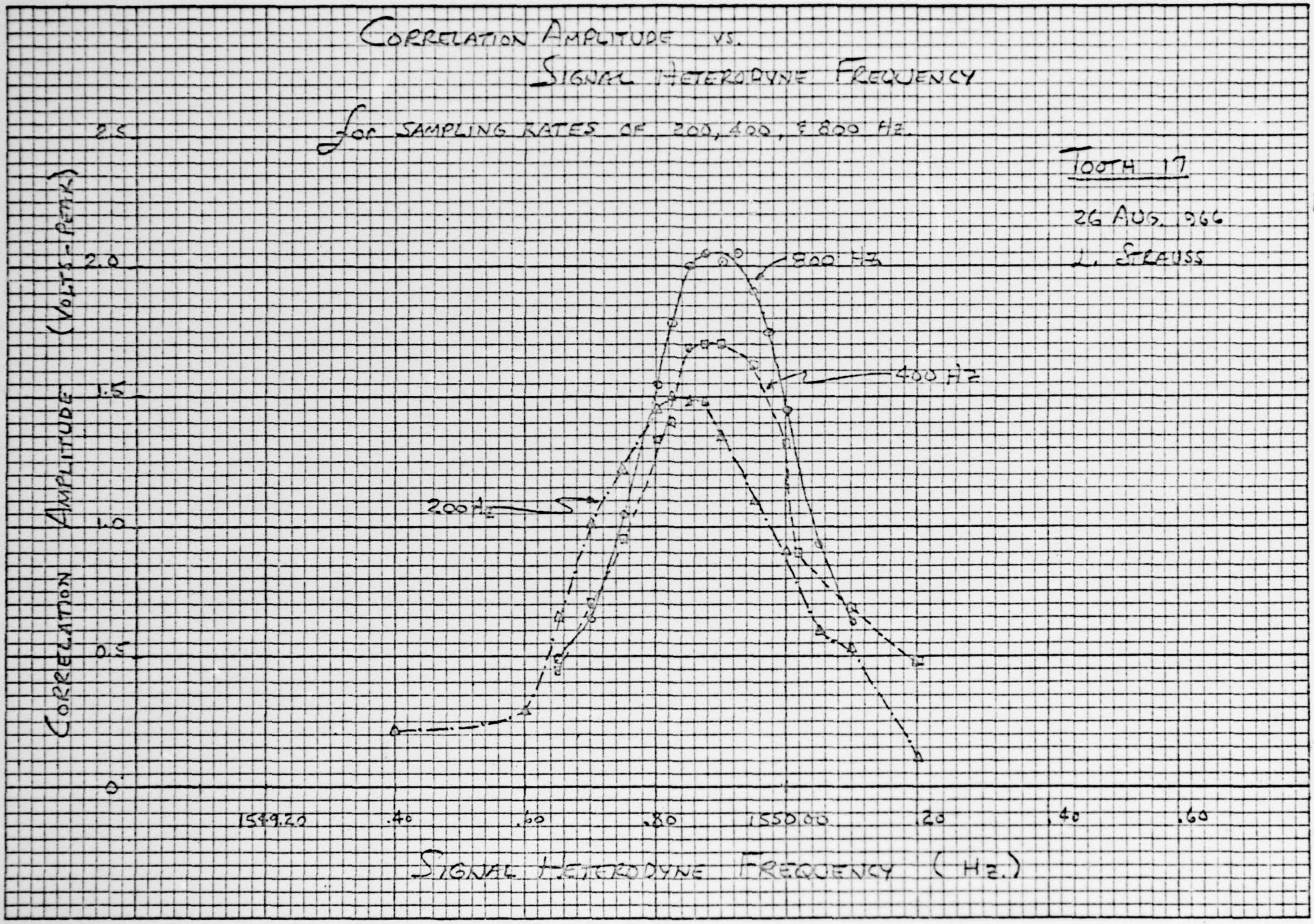

Figure 5. Correlation Amplitude vs. Signal Heterodyne Frequency for Sampling Rates of 200, 400 and 800 Hz for tooth 17

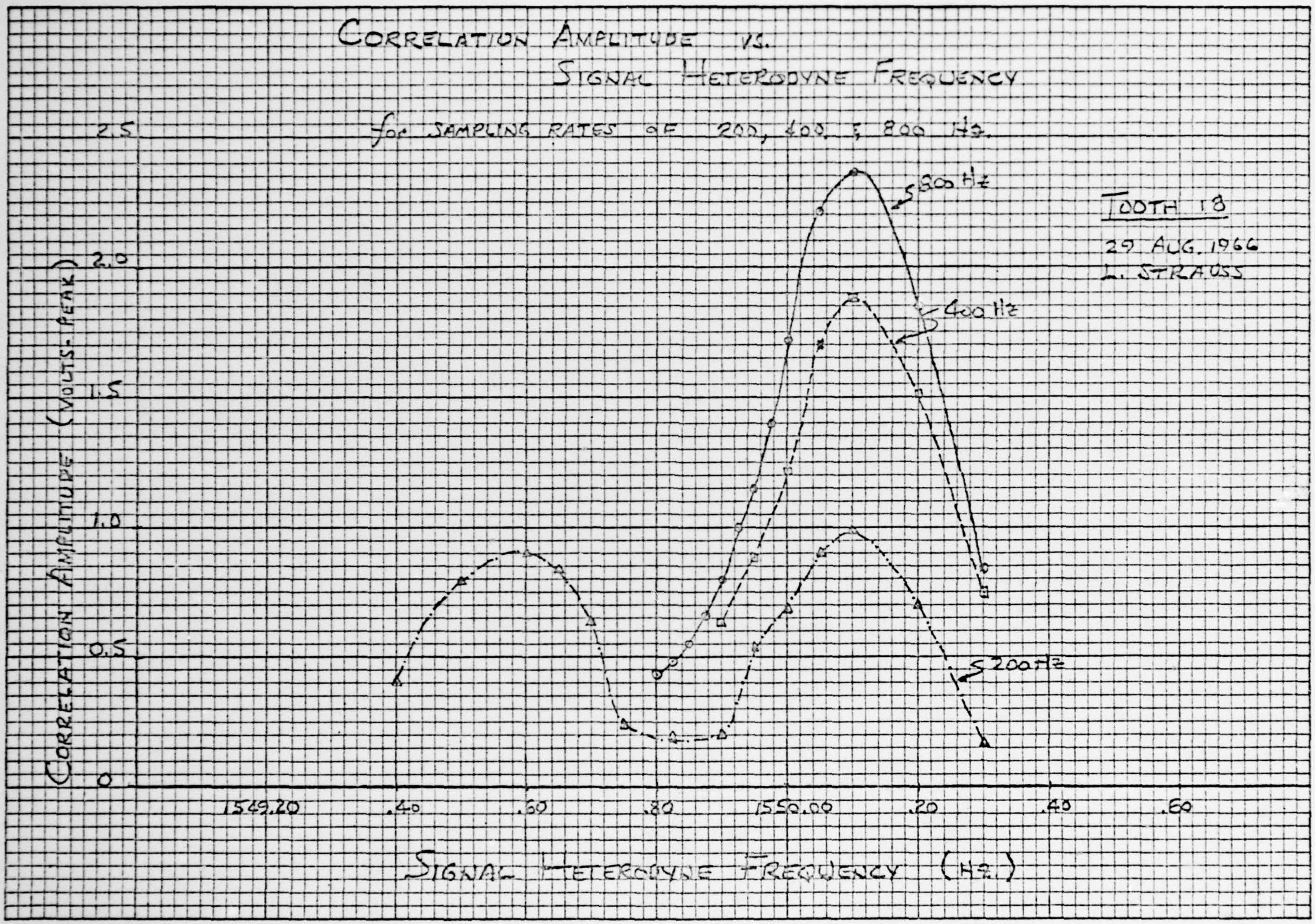

Figure 6. Correlation Amplitude vs. Signal Heterodyne Frequency for Sampling Rates of 200, 400 & 800 Hz for tooth 18

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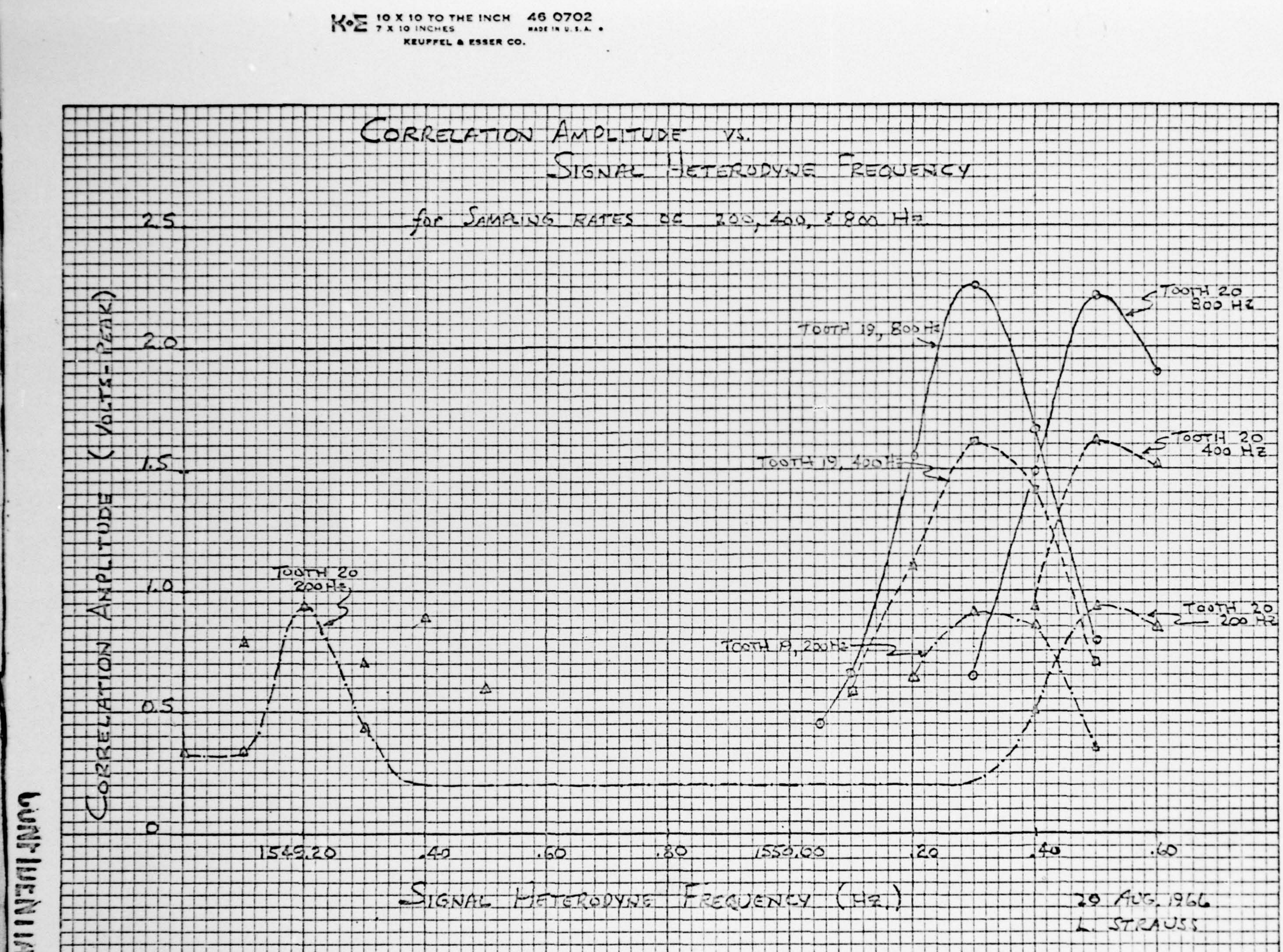

Figure 7. Correlation Amplitude vs. Signal Heterodyne Frequency for Sampling Rates of 200, 400 & 800 Hz for Teeth 19 & 20

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	db Down From 800 Hz Sample Rate	
Sample Rate / Tooth	200 Hz	400 Hz
14	8.3	3.4
15	6.5	1.8
16	7.0	2.1
17	2.8	1.8
18	7.4	1.8
19	8.0	3.0
20	7.3	2.7

Figure 8. Correlation Amplitude for Different Sample Rates

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Tooth	12			13			14			15			16			17			18			19			20			21			22			23		
Sample Rate (Hz) / Freq. (Hz)	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800	200	400	800
4004.00	0.72	1.17	1.58	0.74	1.38	1.56																						0.91								
		0.66	1.02		1.74	1.87		0.57	0.63																											
		0.48			1.60	1.73		0.86	1.08																											
4003.50				0.70			0.64																		0.96											
					1.08	1.26		1.43	1.72			0.45																								
					0.58	0.88		1.85	2.13		0.58	0.72																								
4003.00						0.54	0.78	1.58	1.85	0.63	1.00	1.22										1.01														
								1.36			1.31																									
					0.50			1.01	1.35	0.75	1.53	1.82										0.91														
								0.80		0.98	1.78			0.53					0.61			0.86														
								0.57	0.71	0.95	1.89	2.34		0.61	0.63				0.74			0.65														
4002.50								0.51		0.89	1.74		0.46	0.83					0.91			0.53														
										0.73	1.57	1.91	0.61	1.05	1.12				0.99			0.44														
										0.67	1.43		0.73	1.34		0.47			1.01																	
										0.51	1.08	1.46	0.88	1.64	1.72	0.55		0.54	0.98																	
											0.96		0.89	1.53		0.77			0.84																	
4002.00											0.55	0.72	0.88	1.86	2.27	0.99	0.61	0.64	0.70																	
													0.84	1.74		1.15	0.88		0.56																	
													0.81	1.49	1.95	1.31	1.10	1.26	0.55																	
													0.74	1.19		1.26	1.43		0.46																	
													0.71	0.94	1.24	1.40	1.72	1.82	0.4	0.51	0.57															
4001.50													0.68	0.63		1.18	1.88		0.41	0.58																
													0.84	0.49	0.73	1.26	1.86	2.20	0.47	0.79	0.82															
										0.53			0.86			1.14			0.59																	
										0.46			0.99		0.66	0.86	1.52	1.73	0.70	1.28	1.41															
										0.48			0.96			0.74			0.78																	
4001.00										0.66			0.79			0.60	0.83	1.27	0.90	1.76	1.99	0.45	0.56													
										0.78			0.76			0.46			0.96			0.42														
										0.90			0.56			0.41	0.51	0.60	0.88	1.85	2.35	0.43	0.77	0.84												
										1.05			0.46			0.39			0.78			0.66														
										0.96									0.56	1.32	1.76	0.75	1.27	1.49												
4000.50							0.48			0.91									0.44			0.81														
							0.67			0.77									0.37	0.80	1.04	0.96	1.60	1.99		0.49	0.54									
							0.78			0.74												0.89			0.44											
							0.95			0.50											0.71	0.79	1.70	1.96	0.51	0.76	0.95									
							0.94			0.45												0.70			0.68											
4000.00				0.44			1.01														0.49	0.57	1.11	1.57	0.73	1.31	1.56									
																							0.72	0.71		1.70	2.20		0.55	0.73						
																										1.62	2.11		0.90	1.02						
3999.50	0.43			1.08																								0.65			0.73					
																										1.09	1.44		1.41	1.74			0.42			
																										0.62	1.18		1.83	1.80		0.53	0.65			
3999.00	0.90			0.54																							0.66	0.65	1.58	1.79	0.43	0.93	1.07			
	0.91																											0.54	1.06		0.76	1.46				
																													0.52			1.79			0.62	
3998.50																																				
																																1.51			1.09	
																																0.95			1.55	

Figure 9. Artificially-Dopplerized Target Matrix

CONFIDENTIAL

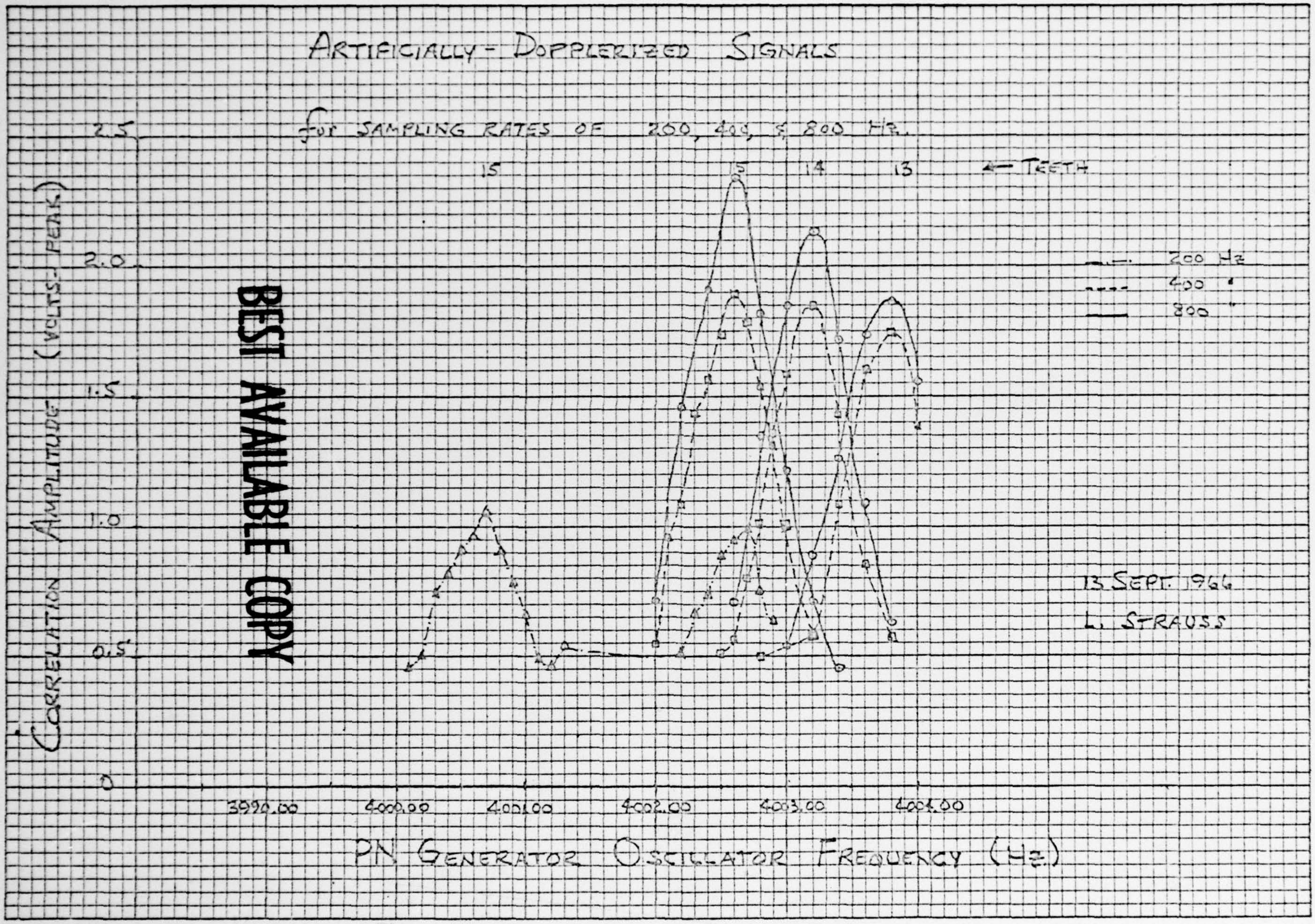

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Figure 10. Artificially-Dopplerized Signals for Sampling Rates of 200, 400 and 800 Hz for Teeth 13, 14 & 15

CONFIDENTIAL

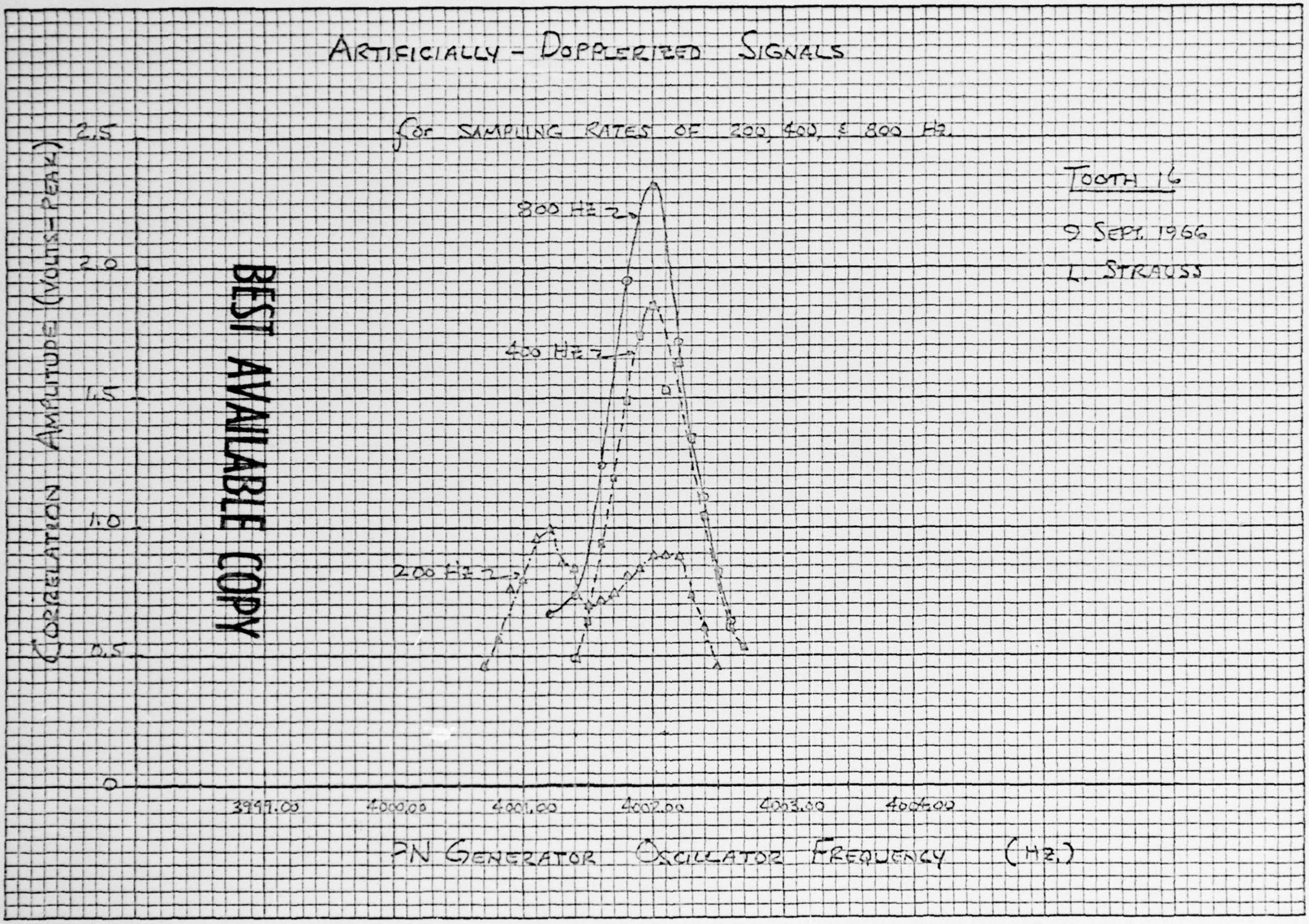

Figure 11. Artificially-Dopplerized Signals for Sampling Rates of 200, 400 and 800 Hz for Tooth 16

CONFIDENTIAL

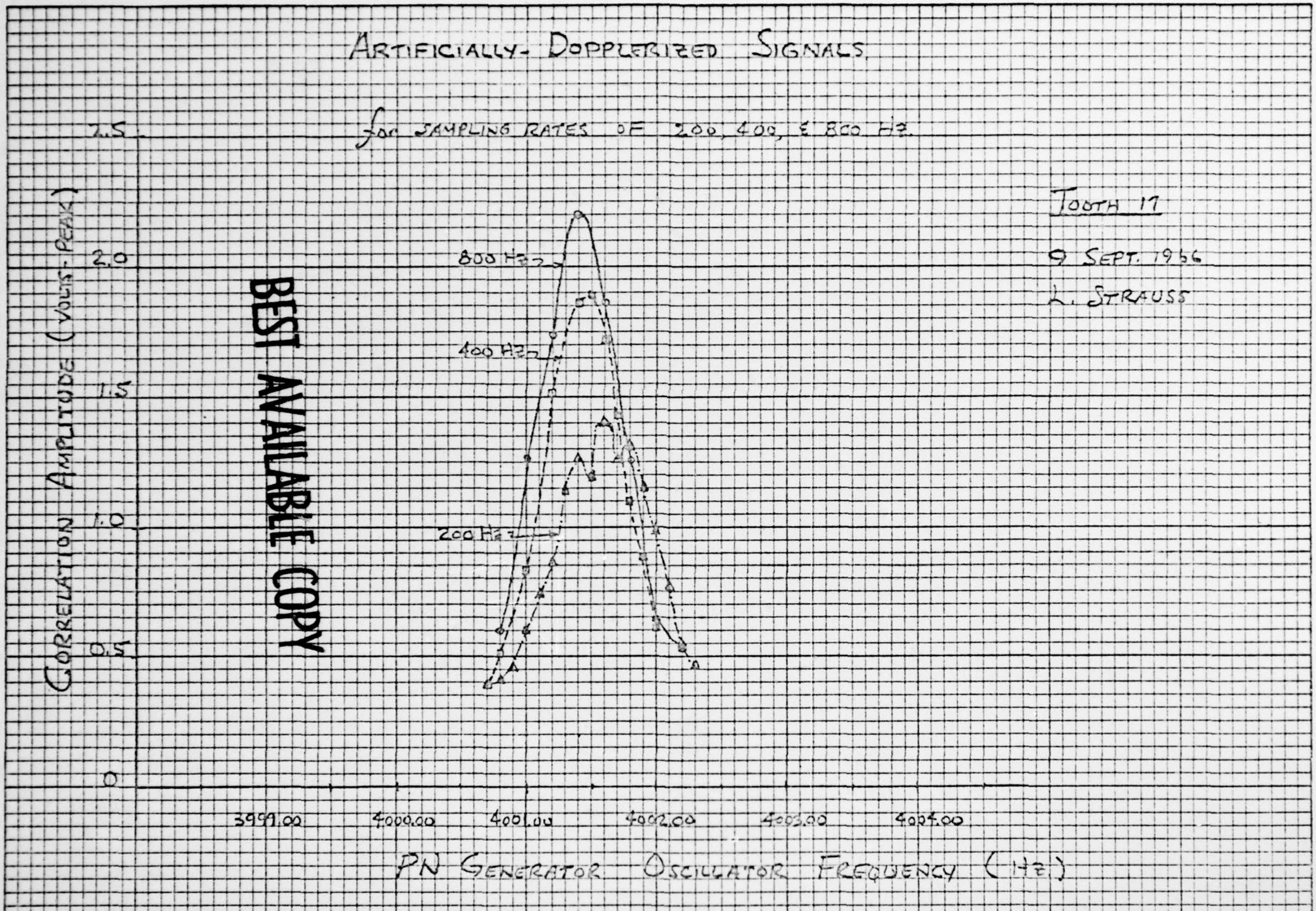

Figure 12. Artificially-Dopplerized Signals for Sampling Rates of 200, 400 and 800 Hz for Tooth 17

CONFIDENTIAL

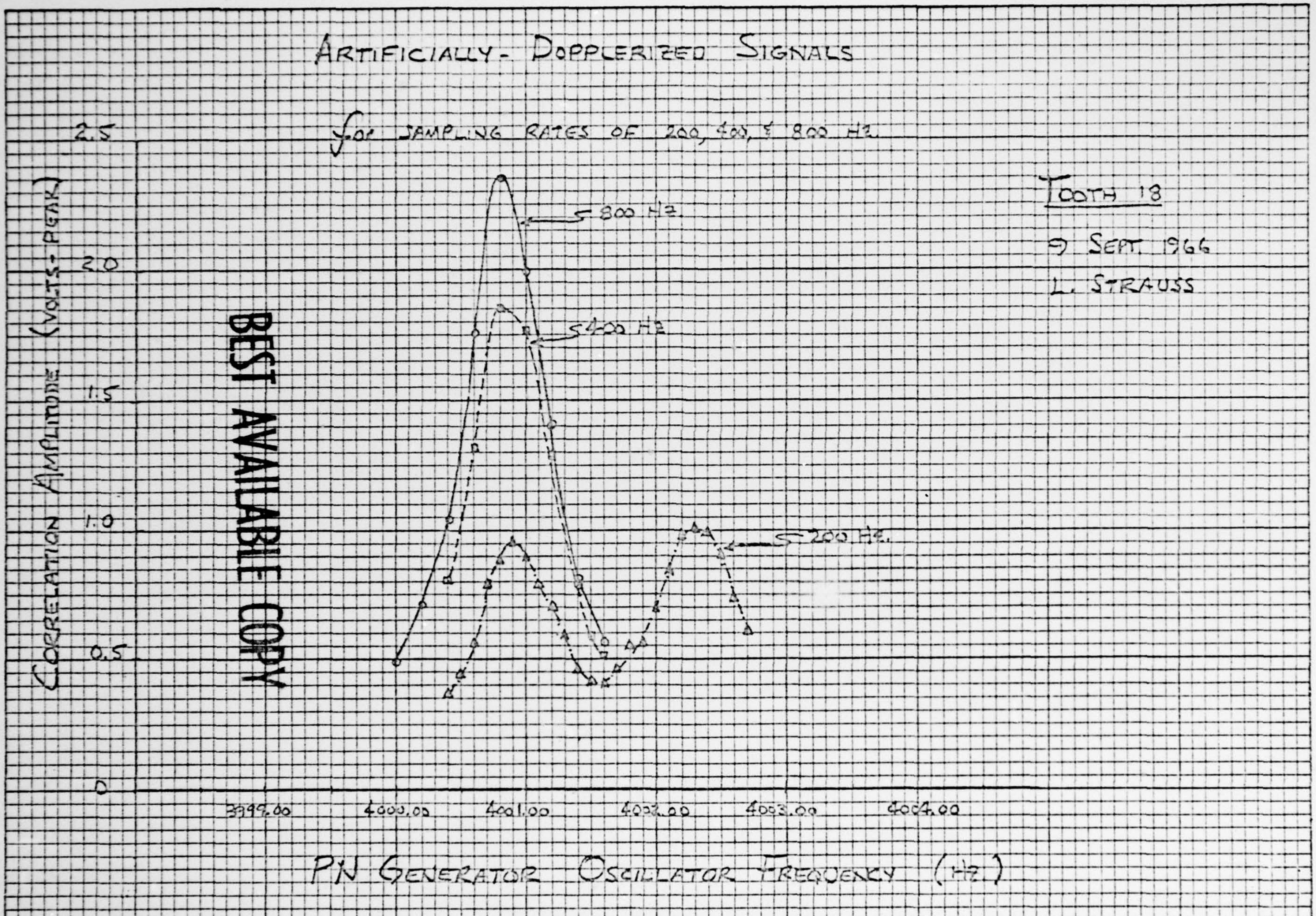

Figure 13. Artificially-Dopplerized Signals for Sampling Rates of 200, 400 & 800 Hz for Tooth 18

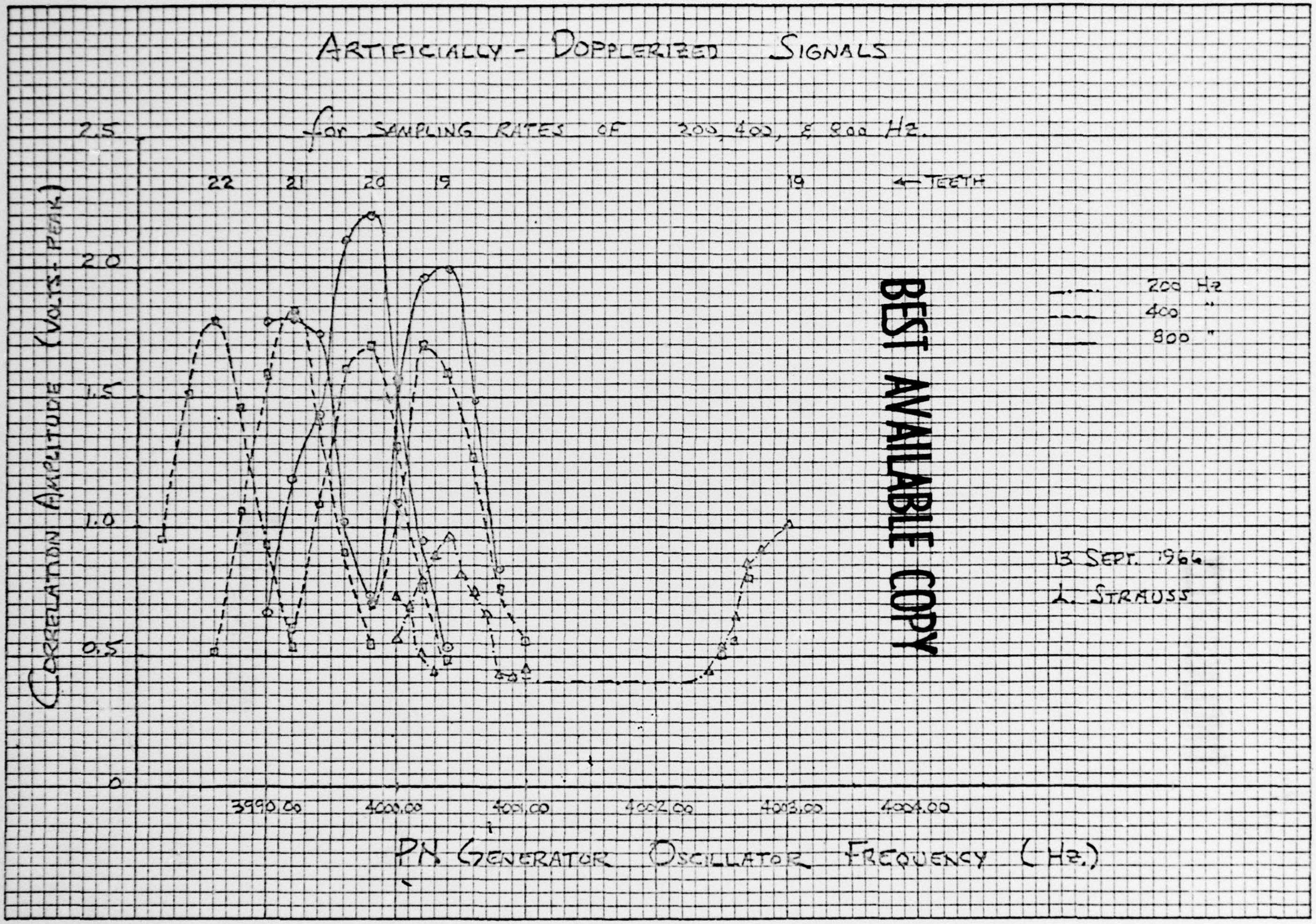

Figure 14. Artificially-Dopplerized Signals for Sampling Rates of 200, 400 & 800 Hz for Teeth 19, 20, 21 & 22